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Final Report for Task 4113
International Ultraviolet Explorer GO Program
P.O. S-97236-E

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This contract involved the investigation of atmospheric parameters of stars, as derived from ultraviolet spectra obtained with the International Ultraviolet Explorer (IUE) satellite. Low-resolution spectra were obtained with both long and short wavelength cameras of the IUE for a group of spectral type B and A stars in order to record the spectral energy distribution in the ultraviolet region. The investigator was present at Goddard Space Flight Center (GSFC) during the observations.

The overall nature of the program, conducted in collaboration with Dr. S. Adelman (Citadel), involves the determination of stellar effective temperature in both normal and chemically peculiar stars by fitting the observed flux distributions with those calculated for known temperatures and chemical compositions. For warm stars, such as those of spectrum type B and A, the majority of flux is found at wavelengths shortward of the atmospheric cutoff. Ground-based spectrophotometry had previously been obtained by Adelman and his collaborators. The low-resolution IUE spectra extended the observed flux distributions down to approximately 1200 angstroms, thereby including nearly all flux from the stars.

The investigator developed a routine to concatenate flux calibrated optical and ultraviolet data into a single spectrum. Then, a new version of the computer code ATLAS/SYNTHE was installed on the VAX machines at GSFC in order to compute model atmosphere fluxes for a variety of effective temperatures. Model atmospheres were fitted to the observations to arrive at a best estimate for the effective temperature. Model atmospheres were then constructed for individual stars so that abundances could be determined from IUE high-dispersion spectra. With atomic line lists developed for Hubble Space Telescope spectral analysis, the investigator determined the abundances of platinuum, gold, and mercury in six stars (kappa Cnc, upsilon Her, mu Lep, omicron Peg, 21 Aql, and nu Cap) via a technique termed 'templating'.

Under separate funding, the investigators are acquiring reprocessed IUE spectra for the targets that were obtained in this program. With the application of newer stellar opacities they will re-evaluate the effective temperatures, as well as the heavy element abundances, as they are likely to have changed as a result of the IUE final archive processing. At a later date a publication that includes the reprocessed data will present all results and methodology.

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USING *HST*/GHRS ECHELLE SPECTRA AS TEMPLATES FOR *IUE* DATA ANALYSIS

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ABSTRACT Echelle spectra obtained with the *HST*/GHRS are used to understand the blending in lower resolution *IUE* sprectra in the region of the raie ultime line of Au II. Laboratory analysis of the Au II transition has provided an accurate wavelength and transition probability from which the first Au abundances are determined for stars other than the Sun.

INTRODUCTION

A wealth of data have been accumulated with the *IUE* satellite that are useful in the determination of elemental abundances in B and A-type stars. Using these data researchers have determined abundances for the elements B, C, N, O, Ga, and Pt to name a few, which otherwise would have been difficult or impossible to derive from ground based data alone. However, the accuracy to which line profiles are synthesized and abundances determined has always been limited both by the *IUE* instrument characteristics ($R = 12{,}000$, $S/N = 10$-20) and lack of knowledge of the atomic data (wavelengths, transition probabilities). We now see the advent of a golden age in UV stellar spectroscopy, ushered in by the high spectral resolution capabilities of the *Hubble Space Telescope* (*HST*) Goddard High-Resolution Spectrograph (GHRS), capable of achieving resolving powers of 90,000 and $S/N > 100$, even in the telescope's present state.

As obtaining observing time with the *HST* is very competetive, it may be several years before many of the problems associated with chemically peculiar (CP) stars can be addressed. However, some of the more basic work, such as defining the elemental abundance distribution patterns in various CP star classes, may be addressed now with a limited sample of GHRS spectra, the *IUE* archives, and a healthy contribution from the atomic spectroscopy community. We illustrate here how our GHRS echelle-resolution spectra of the HgMn stars χ Lupi and κ Cnc can be used as templates for understanding the blending that plagues the study of elemental abundances with *IUE* spectra and report the first accurate abundance determinations for Au in stars other than the Sun.

OBSERVATIONAL DATA

GHRS echelle-B mode (R = 83000) spectra were obtained centered at λ1741 Å, spanning approximately 9.8 Å in wavelength coverage, for the two HgMn stars χ Lupi and κ Cnc. The resultant spectra have S/N ratios of 70 and 50, respectively, in the continuum. Similar spectra obtained near the Hg II λ1942 Å resonance line have been extensively studied by us (Leckrone *et al.* 1991, 1992) for the purpose of determining elemental abundances and Hg isotope mixtures that may constrain theories addressing the origin of chemical peculiarities in CP stars. The absolute wavelength registration at 1741 Å has been accomplished using Mn II transitions measured with the Lund Fourier Transform Spectrometer (FTS) to an accuracy of ± 0.001Å. Relative wavelength measurements within a spectrum are accurate to ± 0.002 Å. Complementing the GHRS data are high resolution (R = 12,000) *IUE* spectra, available from the archives, for several normal and HgMn type stars. The *IUE* spectra are coadditions of nine individual exposures obtained at three locations in the large aperture. This observing strategy has been described by Leckrone and Adelman (1989) and effectively increases the S/N ratio to approximately 40.

SPECTRUM SYNTHESIS

Elemental abundances can only be studied in *IUE* spectra by synthetic spectrum techniques due to the complexity of line blending. Our atomic data are based upon the compilations of Kurucz (1990) with improvements made by both experimental and theoretical means. Wavelengths for many lines were remeasured with the Lund FTS. In only rare instances, where knowledge of important blending components can not be obtained from laboratory or theoretical means, have we employed astrophysically determined gf values. A Ritz wavelength for the Au II raie ultime transition was determined with the Lund FTS. This line shares common lower ($^3D_3$ 5d^9 6s) and upper ($^3F_4$ 5d^9 6p) levels with several transitions that are directly observeable with the FTS and from which accurate energy levels have been measured. Its wavelength was determined to be 1740.476 ± 0.001 Å. Ab initio calculations, by means of a Cowan code, have determined the stength, or transition probability, for this Au II line to be log gf = +0.58. Preliminary laboratory lifetime measurements made at Lund estimate the value to be slightly lower. All work displayed here utilizes log gf = +0.5 ± 0.1 for the Au II line. In the near future we will obtain a more accurate laboratory lifetime measurement; however, the expected change in transition probability should not appreciably change the results presented here. Also, hyperfine structure splitting is extremely small for this transition and has not yet been included in the spectral synthesis calculations.

Figure 1 presents the comparison of GHRS and *IUE* observations with theoretical fits for the same 2 Å spectral segment in the HgMn star κ Cnc. Appropriate Gaussian profiles have been convolved with a theoretical spectrum, generated with the SYNTHE code and ATLAS LTE model atmospheres, to produce the instrumental and rotational broadenings (v sin i = 6 km s^{-1}). The GHRS spectrum has been normalized with the aid of the synthetic spectrum, which identifies spectral regions that are relatively free of line opacity.

The comparisons clearly show: a) that the Au II line is well fit by the synthetic spectrum at an overabundance of nearly +3.6 dex relative to the solar abundance, and b) that missing opacity in the *IUE* spectral fit is attributed to unidentified atomic transitions that are observed, but not fit, in the higher resolution GHRS spectrum. From a GHRS spectrum of χ Lupi (illustrated in Leckrone *et al.*, this volume), a stronger overabundance of Au is determined.

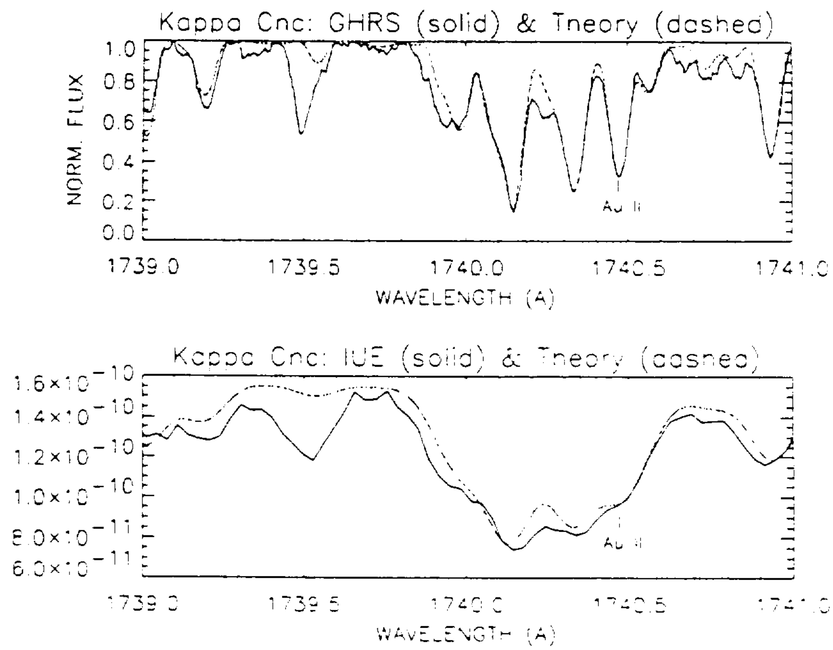

Fig.1. A comparison of GHRS and *IUE* data with synthetic spectra.

By careful analysis of the GHRS spectra, in terms of line identifications and transition probabilities, the problems encountered by the often severe blending in quantitative analyses of IUE spectra can be alleviated. The line list representing the theoretical spectra of Figure 1 *is the template* with which the *IUE* spectra are studied. Figure 2 presents a montage of synthetic spectrum fits (dashed) to *IUE* high dispersion spectra (solid) for the blended spectral feature that includes the Au II line. For each star two theoretical fits are provided: the best fit Au abundance and the solar Au abundance, thus illustrating the effect of the Au overabundance upon the synthetic spectrum. Atmospheric parameters for these stars were taken from the literature (Adelman 1988, 1991, 1992, and Adelman & Philip 1990) and have been derived from high-dispersion optical spectra. Table 1 presents the abundances for Pt, Au, and Hg as determined from either GHRS (χ Lupi, κ Cnc) or *IUE* data (remaining stars). Abundances for Fe and Mn are those of Adelman. Overall, the four HgMn stars (χ Lupi, κ Cnc, υ Her, and μ Lep) display large enhancements in the abundances of the very heavy elements Pt, Au, and Hg relative to the Sun while generally maintaining the odd-even abundance pattern. The mild Am star o Peg displays lesser overabundances. For reference, the solar values are those of Anders and Grevesse (1989). The abundance for Pt in each case except χ Lupi is the most uncertain as many of the Pt lines in Mn-rich stars are blended with Mn features. The Pt abundance in χ Lupi is consistent with that found by Dworetsky, Storey, and Jacobs (1984). Upper limits have been placed on the Hg abundance in the normal stars 21 Aql and ν Cap. Their possible enhancements relative to the Sun may reflect either the uncertainty in the solar Hg abundance or an enrichment of the material from which these stars formed. The Hg abundances have been determined from the Hg II λ1942 Å resonance transition in a manner similar to that for Au in each of the stars presented. Details of this analysis will be presented elsewhere.

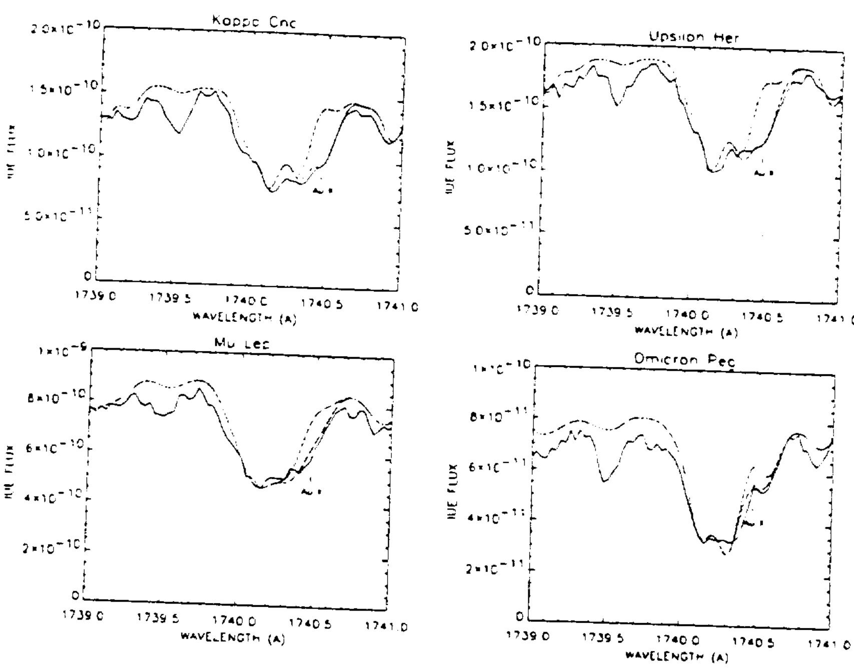

Fig.2. Au II synthetic spectrum fits.

CONCLUSIONS

It has been shown that limited high-resolution UV spectra obtained with the GHRS can be used as a tool in understanding a larger sample of stars for which data are available from the *IUE*. The accuracy of abundance determinations utilizing *IUE* high-dispersion spectra can be improved to approximately ± 0.1 dex providing the data are of good quality and, more importantly, the blending contributors are well understood. In this context we have determined the abundances of Pt, Au, and Hg in several HgMn stars and one Am-like star, in all cases finding overabundances.

TABLE 1
Pt, Au, and Hg Abundances in Normal and Chemically Peculiar Stars

Star	[Fe/H]	[Mn/H]	[Pt/H]	[Au/H]	[Hg/H]
Sun	+0.00	+0.00	+0.00	+0.00	+0.00
χ Lupi	+0.07	+0.15	+4.29	+4.05	+5.00
κ Cnc	−0.17	+2.22	+3.50	+3.58	+4.55
υ Her	−0.45	+1.55	+4.00	+3.30	+4.85
μ Lep	−0.06	+1.89	+3.70	+2.70	+5.02
o Peg	−0.20	+0.45	+1.40	+1.00	+1.40
21 Aql	−0.43	−0.52	–	–	<+0.5
ν Cap	−0.19	−0.08	–	–	<+1.0

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